

Interferometry from Space

From DUCollab

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Introduction/Why Space Interferometry?

Given the extra expense and the increased difficulty of access to interferometers in space, it is logical to ask "why would one want to build and operate interferometers in space?". In fact, there are many strong reasons for basing interferometers in space. For instance:

- observations are possible at wavelengths not accessible from the ground (x-ray, UV, far-IR, sub-mm)
- it is possible to observe continuously over periods of days to weeks
- the entire primary array can be tilted to point at the target, thus avoiding the need for the long delay-lines required on the ground for off-axis observations
- there is a limitless potential for very long baselines
- reconfigurations of the primary array are relatively easy
- the more stable environment enables easier alignment and calibration
- lack of an atmosphere and of turbulence enables longer integrations
- passive cooling of IR instruments is possible
- there is more control and understanding of the facility, e.g. vibration control easier and more easily understood and there is no windshake

Notional Path for Development of Space Interferometry

The exact development path for Space Interferometry is uncertain as of this writing due to delays in several significant projects (e.g., ST-9, SIM, TPF-I), but nevertheless it is still possible to display a "notional" path for a logical development flow. Figure 1 shows such a path, starting with existing ground-based interferometers and testbeds developing technologies needed for future space-based interferometers, through small space interferometers such as FKSI and Pegase and the Pathfinders (MAXIM-PF, SI-Pathfinder, SPIRIT) for the larger strategic missions, to the astrometric missions Space Interferometer Mission (SIM) and Terrestrial Planet Finder - Interferometer (TPF-I), and leading, finally, to the ultimate goal: the true ultra-high resolution imagers such as Stellar Imager (SI), Life Finder (LF), Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), Black Hole Imager (BHI/MAXIM) and Planet Imager (PI).

Notional Path for Development of Space Interferometry

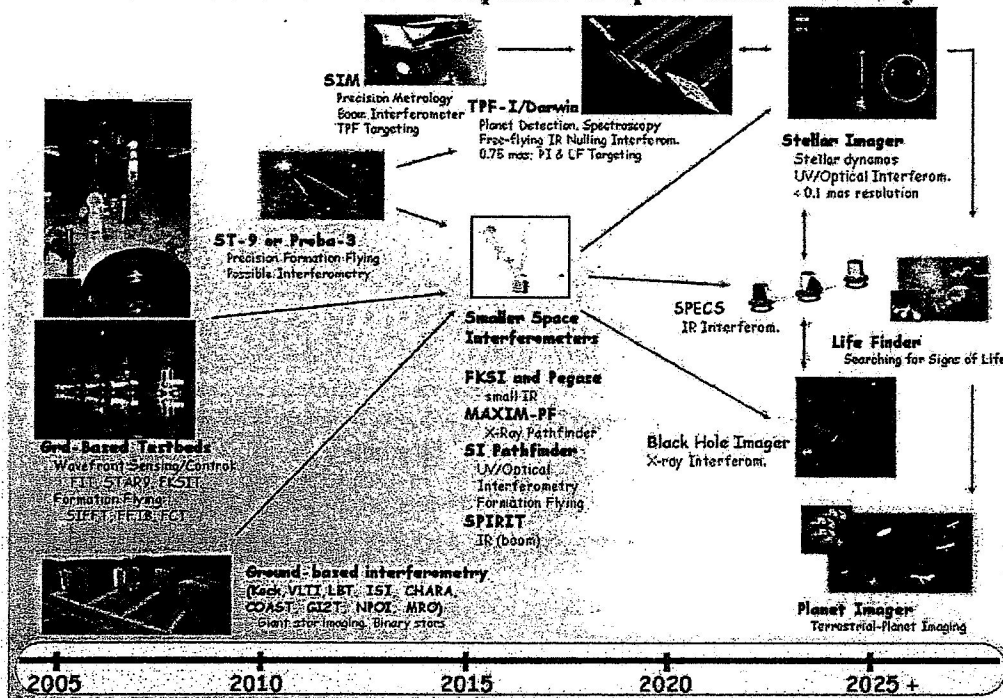


Figure 1: A notional path for the development of space interferometry. (Courtesy: K. Carpenter/NASA).

Technology Development for Space Interferometers

There are a large number of ground-based laboratory "testbeds" devoted to developing technologies that will be to enable space interferometers. These testbeds are concentrated on 4 major technology areas: wavefront sensing and control of sparse arrays, image synthesis from interferometric or sparse aperture data, precision formation flying of a many-element array, and nulling of interferometric signals to enable detection of faint sources (e.g. planets) next to bright ones (parent stars).

The NASA/Goddard Space Flight Center (NASA/GSFC) Fizeau Interferometer Testbed (FIT; Carpenter, Lyon, Liu, Mozurkewich, Dogoda et al.) is developing nm-level closed-loop optical control for large arrays (7-18 separate articulated apertures) based on analysis of science data stream, to enable UV/optical/x-ray Fizeau imaging interferometry (e.g., for missions such as SI, BHI/MAXIM, LF, PI).

The LMATC STAR-9 Testbed is developing wavefront sensing and control for a "somewhat sparse" array (fill-factor ~ 28%).

The GSFC Wide-field Imaging Interferometry Testbed (WIIT; Leisawitz, Rinehart et al.) is demonstrating the use of a detector array for spatial multiplexing in a Michelson optical/IR interferometer, to enable far-IR imaging of arc-minute-scale fields of view at high resolution, while simultaneously providing spectral information. It will enable far-IR interferometers, such as SPIRIT and SPECS, but is also applicable to TPF-I.

The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT; Carpenter, Lyon, Stahl, Miller et al.) is developing and demonstrating algorithms for autonomous precision formation flying. It will be demonstrating: Formation Capture (deployment), Maintenance and Reconfiguration, and Synthetic Imaging maneuvers, by using the MIT-developed SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) experiment on the Marshall Space Flight Center (MSFC) Flat Floor Facility.

The JPL Formation Control Testbed (FCT; A. Ahmed, J. Keim, J. Shields) uses multiple 6-degree-of-freedom robots on air-bearings with on-board guidance and control (G&C) capability for development and validation of Formation Flying control architectures and algorithms. It is demonstrating Formation Acquisition, Observation-on-the-fly maneuver, and Collision Avoidance.

The GSFC Formation Flying Testbed (FFTB; J. Leitner, J. W. Mitchell, R. J. Luquette) is a hardware-in-the-loop test environment for formation navigation and control. It is a modular, hybrid, dynamic simulation facility for end-to-end Guidance, Navigation and Control (GN&C) design and analysis of formation flying spacecraft.

The Fourier-Kelvin Stellar Interferometer (FKSI) Optics Testbed (Danchi et al.) is a nulling interferometer that will obtain a null depth~10⁻⁴, perform verification of fiber "wavefront clean up" with a variety of fiber characteristics and specifications, perform sensitivity studies, and develop an alignment plan and procedures for a nuller.

The TPF Planet Detection Testbed (Stefan Martin) demonstrates deep, stable nulling and planet detection, by simulating a dual chopped Bracewell interferometer. It is comprised of a four beam star and planet source and nulling beam combiner. It has many control systems designed to achieve stability of alignments and optical path differences over long periods of time. Interactions between designs for phaseplate systems that achromatically invert the electric field of one of each pair of the incoming beams to achieve the null and the choice of fringe tracking schemes is being investigated.

A selection of these testbeds are shown in Figure 2.

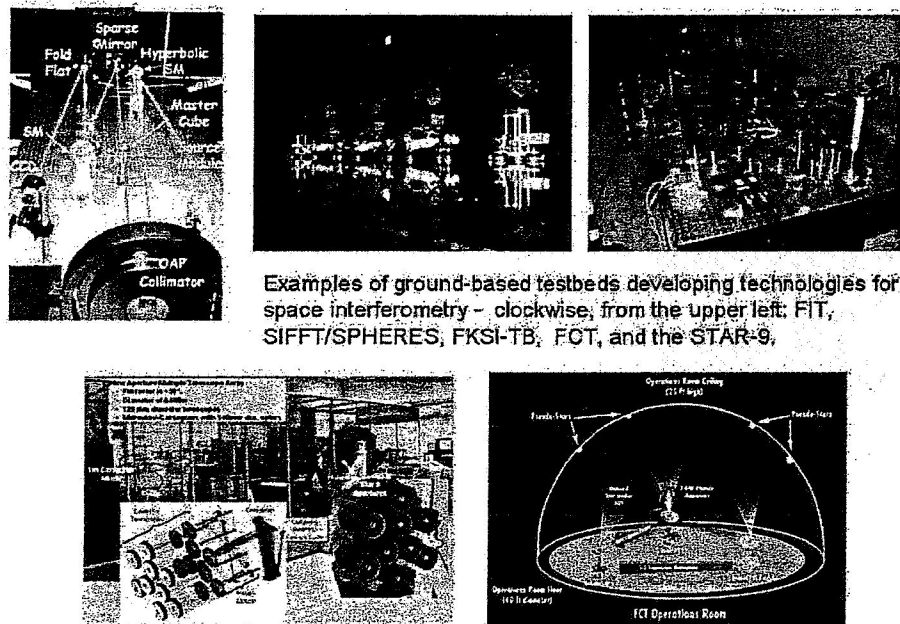


Figure 2: Examples of ground-based testbeds developing technologies for space interferometry. (Courtesy: NASA/GSFC, NASA/JPL, and LMATC).

Missions in Technology Study Phase

There are two major space missions which are currently in the "Technology Study Phase". These missions perform precision astrometry (measurement of the position of celestial objects) and planet detection.

The Space Interferometry Mission (SIM) was a key mission in NASA's Origins Program. It is designed to perform precision astrometry on stars to V=20 (a visual wavelength astronomical magnitude). It is an optical interferometer on a 9-m structure, with one science interferometer, and two guide interferometers. Its global astrometric accuracy is 4

microarcseconds (μas). By the end of its intended 5-year mission lifetime, its narrow-field astrometric accuracy would be $1 \mu\text{as}$, in a single measurement. Typical observations take about 1 minute and about 5 million observations would be obtained in 5 years. It would not perform any imaging or nulling of starlight.

The Terrestrial Planet Finder – I (TPF-I) (or the European Space Agency (ESA) equivalent IRSI-Darwin) are designed to detect Earth-like planets, perform spectroscopic analysis on planetary atmospheres, and perform synthetic imaging and astrophysics. It is an IR Nulling interferometer that would survey stars within about 30 parsecs over a five year mission duration. It consists of four collector spacecraft and one combiner spacecraft, and would orbit around the Sun-Earth L2 point. It would utilize a 45-135 m baseline for planet-finding and <1 km baseline for astrophysics. (An alternative formulation of the TPF mission would utilize a single telescope and coronagraph (TPF-C) at optical wavelengths to do similar science. No decision has been made whether to fly one or both missions, if either, at this time.)

Both missions have recently been downgraded to "Technology Studies", but will hopefully be re-instated as full missions in the future, as funds become available within NASA and/or ESA.

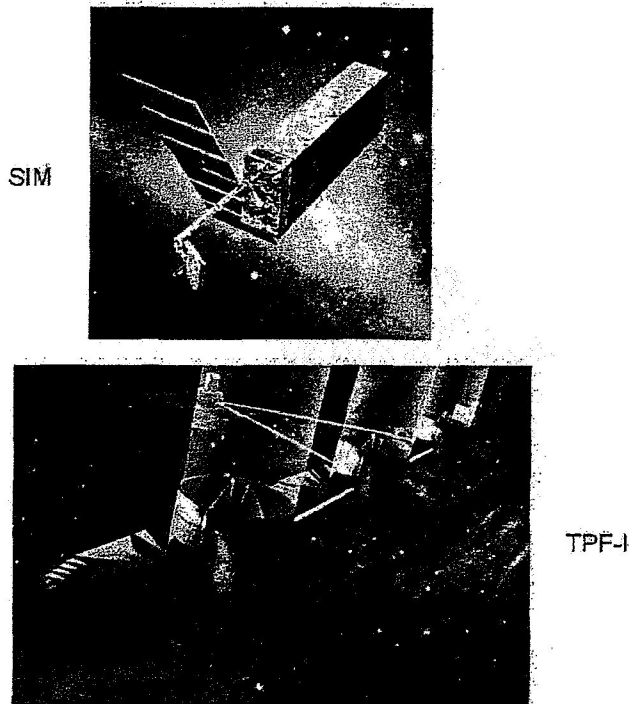


Figure 3: Artist's concepts of the SIM (top) and TPF-I (bottom) missions. (Courtesy: JPL/NASA).

On the Path Toward the "Vision Missions": Probe-Level Mission Concepts

The goals of these more modest missions would be to perform good science at more moderate costs than the full-up Vision/Strategic missions and to enable technology development and demonstration of those technologies needed for the Large missions. Examples of such mission concepts and candidates for future flights are: FKSI, PEGASE, SPIRIT, SI-PF, and MAXIM-PF.

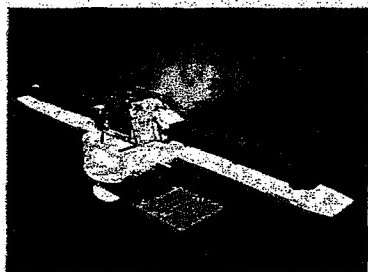
The Fourier Kelvin Stellar Interferometer (FKSI) is composed of ~ 0.5 m telescopes passively cooled to $<70\text{K}$, and has a 12.5 m baseline, operates in the 3 – 8 (or 10 TBR) micron science band, but utilizes the 0.6-2 micron band for fringe and angle tracking. It would have a null depth better than 10^{-4} (floor), 10^{-5} (goal) and perform $R=20$ (wavelength/delta-wavelength or resolution) spectroscopy on the nulled and bright outputs of the science beam combiner. Its science goals are to: detect >20 Extra-solar Giant Planets, Observe Circumstellar Material (exo-Zodi, debris disks), Star formation (Evolution of circumstellar disks, morphology, gaps, rings, etc.), Extragalactic astronomy (AGN nuclei). The contact for this mission is Bill Danchi/NASA-GSFC.

PEGASE is composed of 3 formation flying satellites in orbit about the Sun-Earth L2 point. It includes two 40-cm telescopes passively cooled to 55 K, with baselines of 2x25m, 2x250m, or 2x500m. It has a fringe sensor (0.5-1.5 micron range) for optical path control and visibility measurements, 2 siderostats to bring the optical beams to a central beam combiner, and is designed for a 2-3 year mission lifetime. Its science goals include: spectroscopy of hot, giant exoplanets (Pegasides), spectroscopy of brown dwarfs, circumstellar disks, dust tori in AGN nuclei; gas envelopes, stellar wind dynamics, debris disks, exo-zodi; coronal line emission from active stars. Contact for this mission is ESA/CNES.

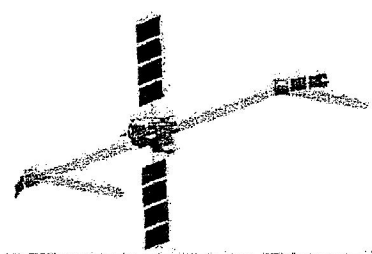
The Space Infrared Interferometric Telescope (SPIRIT) is a precursor to SPECS and would be capable of 0.3" imaging, $R \approx 3000$ spectroscopy with a 1 arcminute FOV over a range of 25 – 400 microns. It has two 1 m telescopes moving along a rotating boom for dense Fourier u-v plane sampling, a scanning optical delay line for spectroscopy ("double Fourier"). Its sensitivity is limited by astrophysical backgrounds, with its optics cryocooled to 4 K. It could be launched into a Sun-Earth L2 orbit as early as 2015 - 2020. Its science goals are to: learn how planetary systems form & acquire their chemical organization, to image the structure in debris disks to understand how and where planets form, to learn how high-redshift galaxies formed/merged. The contact for SPIRIT is Dave Leisawitz/NASA-GSFC.

The Stellar Imager Pathfinder (SI-PF) is a small UV/Optical Space Interferometer with 3-5 free-flying or boom-mounted spacecraft with baselines of about 50 m. It would perform beam combination with UV light and demonstrate true imaging interferometry. It could be launched within a decade after getting a "new start". Such a mission with a small number of spacecraft requires frequent reconfigurations and thus limits observations to targets whose variability does not preclude long integrations but nevertheless tests most of the technologies needed for the full-size SI. The science goals of this mission are to: enable significant new science by exceeding HST's resolution by about 20x, including surface imaging of the apparently largest stars, interacting binary systems, central regions of AGN's, etc. The contact for this mission is Ken Carpenter/NASA-GSFC.

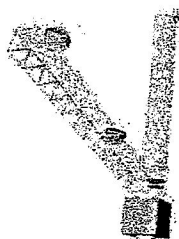
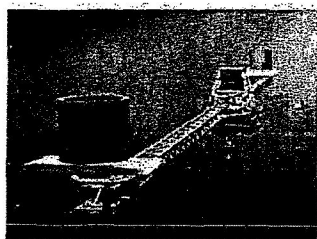
The MAXIM-Pathfinder (MAXIM-PF) mission is composed of two formation-flying spacecraft separated by 500 km and would provide 100 micro-arcsec resolution ($1000\times >$ Chandra telescope), utilizing a 1 to 2 m baseline, with optics on a single spacecraft. Its science would be to image nearby stars at x-ray wavelengths. The contact for this mission is Keith Gendreau/NASA-GSFC.



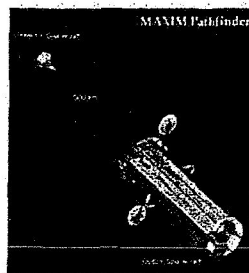
FKS
SPIRIT



PEGASE



SI-PF



MAXIM-PF

Figure 3: Example "Probe" level interferometric mission concepts. (Courtesy: NASA/GSFC and ESA/CNES).

The Ultimate Goal: True Ultra-High Resolution Imagers (Large, Strategic "Vision" Missions)

These missions are the true ultra-high angular resolution imagers, whose goals are to perform amazing science, but whose size and complexity represent "Great Observatory"+ mission level costs and efforts. Implementation of these or similar missions will require dedication over a long timescale, but the potential rewards are nearly infinite. Examples of such missions are SI, SPECS, BHI/MAXIM, LF, and PI.

The Stellar Imager (SI) is a UV-Optical Interferometer that will provide 0.1 mas imaging (+ spectroscopy) of stellar surfaces and interiors, interacting binaries, SN, AGN, QSO's, etc. Its design includes 20-30 "mirrorsats" formation-flying with a beam combining hub, baselines of 100 - 1000 m, and a mission duration on the order of 10 years. It is included as a "Flagship" (Vision) mission in the 2005 Sun Solar System Connection (SSSC) Roadmap and as a candidate "Pathways to Life Observatory" in the 2005 Exploration of the Universe Division (EUD) Roadmap and could be launched in the 2024-2030 timeframe to a Sun-Earth L2 orbit. Its science goals are to study the magnetic field structures that govern: the formation of stars and planetary systems, the habitability of planets, space weather, and transport processes on many scales in Universe. The contact for this mission is Kenneth Carpenter/NASA-GSFC. See also the separate Stellar Imager entry in this Encyclopedia.

The Sub-mm Probe of the Evolution of Cosmic Structure (SPECS) would provide 0.01 aresecond imaging, $R = 3000$ spectroscopy in a 1 arcminute field of view over the 40 – 640 micron spectral range, utilizing baselines up to 1 km. It could launch into a Sun-Earth L2 orbit in the 2025 – 2030 time period. Two 4 m afocal telescopes are deployed in tethered, rotating formation to provide dense Fourier u-v plane sampling. It utilizes a scanning optical delay line for spectroscopy ("double Fourier"). Its sensitivity is limited by astrophysical backgrounds, with its optics cooled to 4 K. It was recommended in the 1990's Decadal Report for investment in technology and as a successor to SAFIR and by the IR astronomical community in the "Community Plan for Far-IR/Submillimeter Space Astronomy". Its science includes the definitive identification of structures in protostellar disks and it will probe the atmospheres of giant planets, image the dust in debris disks, probe the epoch of the formation of the first stars, heavy elements, and dust, and study processes that influenced the history of galaxy formation. The contact for this mission is Dave Leisawitz/NASA-GSFC.

The Micro-arcsec X-ray Imaging Mission/Black Hole Imager (MAXIM/BHI) would provide 0.1 microarcsec x-ray imaging, utilizing baselines up to 10 km, with a beam combiner 50,000 km distant. It would be launched into a Sun-Earth L2 orbit. It would provide 1,000,000x the resolution of HST! Its primary science goal is to directly image at x-ray wavelengths a black hole event horizon. The contact for this mission is Keith Gendreau/NASA-GSFC. For more information see: <http://maxim.gsfc.nasa.gov>

Life Finder (LF) is a successor mission to TPF and is designed to search for spectroscopic signs of life on extra-solar planets. It consists of a large array of telescopes flying in formation and will combine infrared light to produce high-resolution spectra of the atmospheres of extra-solar planets. Its science goals are to enable a search for markers of biological activity, such as seasonal variations in the levels of methane and other gases, changes in atmospheric chemistry and spectral variations in the dominant biomass. Contact for this mission is JPL/NASA.

The Planet Imager (PI) mission concept is an *interferometer composed of interferometers*: 5 formation flying interferometers, each composed of five 8-m mirrors (to yield 25x25 pixel images). It is designed to achieve the Ultimate Goal of NASA's Origins Program: to obtain resolved images of terrestrial-type planets around other stars. Contact for this mission is JPL/NASA.

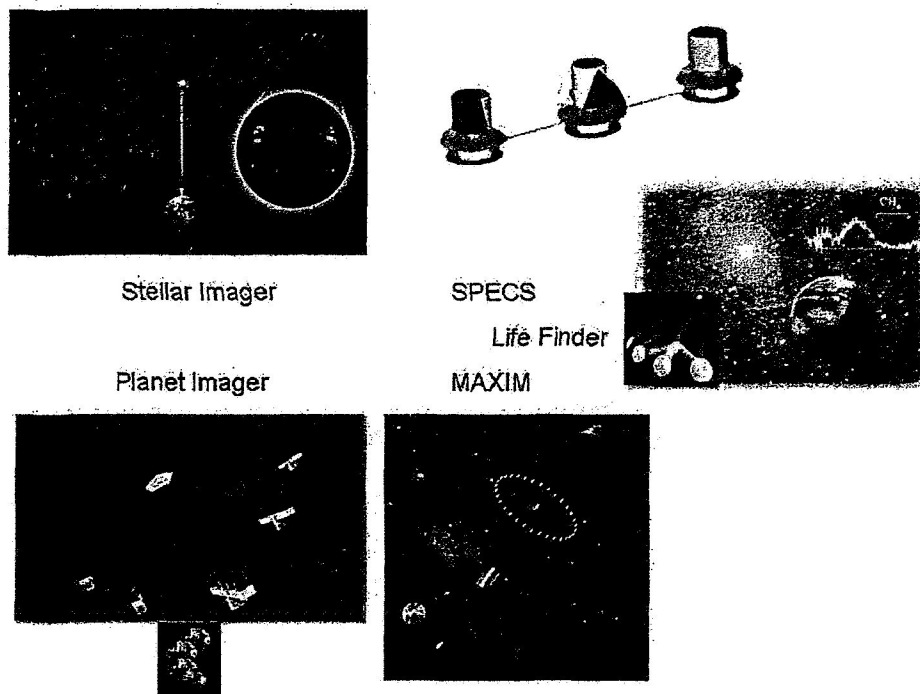


Figure 4: Examples of interferometric "Vision Missions" - true, ultra-high angular resolution imaging observatories. (Courtesy: NASA/GSFC and NASA/JPL).

Summary

Space-based interferometric observatories will be challenging projects, equal at least to that of building the Great Observatories (the Hubble Space Telescope (HST), Spitzer Space Telescope (SST), Chandra X-ray Observatory, and the Gamma Ray Observatory), if not the Pyramids of Egypt - but they represent the next logical step in examining our Universe at substantially higher angular resolution. Increasing our resolving power by factors of 100 or more (as is needed to make meaningful improvements in this observational arena) over existing facilities such as HST and SST requires mirror diameters (100's to 1000's of meters) much larger than can be supported by single or segmented mirrors - and thus the design and construction of sparse aperture, interferometric arrays such as those described herein will be required. But just imagine the rewards of being able to see, for the first time, the surfaces of other stars, the location and type of extrasolar planets and even pictures of those same planets, the inner workings of Active Galactic Nuclei, the close-in details of supernovae explosions, black hole event horizons, and the infrared universe at the same resolution of the UV-optical Hubble Deep Fields. As a slight variation on the "Star Trek: Enterprise" theme song might say, it'll be a "long road, getting from here to there", but it will one well-worth taking.

Workspace Main Page

Article initiated by Ken Carpenter

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